AP Chemistry
Nuclear Chemistry Notes

Radioactivity:

Serendipitous discovery by Antoine Becquerel in 1896
Working with fluorescent compounds
Exposure of photographic film from Uranium Ore
1903 Nobel Prize

Ernest Rutherford 1919
Transmutation of Nitrogen into Oxygen
Bombarded Nitrogen with α particles

Radioactive substances (those w/ unstable nuclei) spontaneously decay into other substances with the emission of particles and energy

Many radioactive elements and their characteristics were discovered by the Curies (Marie, Pierre and Irene (daughter))
-Ex. Radium, Polonium and the positron
-The element Curium and the radiation unit the "Curie" are and their characteristics were named in their honor.
-Marie died of leukemia probably as a result of her work
-She is the only person to win Nobel prizes in both physics and chemistry

Radioactive isotopes = Radioisotopes

Types of Nuclear Reaction Particles

Name	Symbol(s)	Mass	Charge	Special
Alpha	α, ${}^{4}_{2}He$	4	+2	Helium nucleus
Beta	β, ${}^{0}_{-1}e$	0	-1	electron
Neutron	n, ${}^{1}_{0}n$	1	0	
Positron	${}^{0}_{+1}\beta$, ${}^{0}_{+1}e$	0	+1	Positive electrons

In the decay process the nuclear mass (A) and/or nuclear charge (Z) changes.

Use left hand superscripts and subscripts to represent atomic mass (A) and number (Z), respectively ${}^{A}_{Z}X$ (i.e. ${}^{122}_{86}Rn$)

Important Nuclear Related Elements:
Bismuth (Z=83) is the last element with a nonradioactive isotope
Uranium (Z=92) is the last naturally occurring element

Nuclear Reaction Summary:

In writing equations for nuclear reactions the total **mass and nuclear charge MUST be conserved**

Radioactivity for isotopes of light elements (See the neutron to proton ratio chart in your book to determine which isotopes of an element are "stable"[i.e. the stability strip])
The stability of the nucleus is related to the neutron to proton ratio (n/p or N/Z)

If the mass of an isotope is greater than the average mass of that element (listed on the periodic table) then stability is generally achieved through **beta** emission

$^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + ^{0}_{-1}\beta$ Note that the number of neutrons decreases by one and the number of protons increases by one as a neutron is turned into a proton. Charge is conserved by the production of a negatively charged electron (beta particle.

Conversely, isotopes that are lighter than average achieve stability through **positron** emission

$^{A}_{Z}X \rightarrow ^{A}_{Z-1}Y + ^{0}_{+1}\beta$ Note that a proton is turned into a neutron with charge being conserved through the production of the positive electron (positron)

Atoms can also achieve this effect through the process of **electron capture**

$^{0}_{-1}\beta + ^{A}_{Z}X \rightarrow ^{A}_{Z-1}Y$ Here, the capture of an electron allows the proton to turn into a neutron (increasing the N/Z (neutron to proton) ratio)

For elements up to Z=20 the stable ratio is about 1:1
In general, for Z up to 83
Use relative atomic mass to determine stable n/p ratio
Isotopes with even numbers of each nucleon (p and n) are more stable (60% vs. 1.5% for odd p and/or n) Isotopes with Z>83 generally decay through alpha decay

If the atom is too massive overall, then **alpha emission** is likely

$^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + ^{4}_{2}\alpha$ In this case the atom fragments. The atomic number goes down by two, the mass number goes down by four, and an alpha particle (helium nucleus) is released.

Often times high energy is also emitted during radioactivity decay
Gamma rays (γ)
X-rays
These are generally not written into the equation

A **radioactive disintegration series** plots the steps that an unstable element goes through to achieve stability

Natural Radioactive Isotopes
Polonium (84) through Uranium (92)
(ex. Radon-222, Radium-226, Uranium-238, Potassium- 40)

Transuranium Elements (artificial)
-Neptunium (Np, 93) through Meitnerium (Mt, 109)
-Many are used for medical purposes (see Table 3.1)
-Neutron activation analysis is the analysis of a sample by bombarding it with neutrons to create artificial isotopes. As these isotopes decay back to the original elements the rates of decay can be used to identify in excess of 20 or more elements

Example problems:
1. The radioisotope Rb-90 will decay through what type of decay?
2. An isotope with Z>83 will generally decay through what process?
3. What nuclide completes the following nuclear reaction?

$${}^{216}_{84}\text{Po} \rightarrow ? + {}^{4}_{2}\text{He}$$

4. Explain why the isotope ${}^{42}_{21}\text{Sc}$ is unstable.
5. Predict the nuclide that completes the following nuclear reaction

${}^{26}_{13}\text{Al} \rightarrow {}^{0}_{1}\beta + ?$

Disintegrations per second (dps)

Rate (dps) = (Constant)(# of radioactive nuclei)
= kN (k = rate constant s^{-1})

$R = kN$
$R = -dN/dt$
$dN/dt = -kN$
$dN/N = -kdt$
$\ln N = -kt + c$
$N = e^{-kt+c}$
$\mathbf{N = N_0e^{-kt}}$

or as the book leaves it;

$\mathbf{\ln (N_0/N_t) = kt}$

The equation may also be multiplied through by k to arrive at $R = R_0e^{-kt}$, at times a more useful form of the equation.

The unit the Curie was once defined as the activity of one gram of radium. It is now defined more uniformly as 1 curie (Ci) = $3.7\text{x}10^{10}$ decays/s

Half life: The time for ½ of the original sample to decay.
$\mathbf{t_{1/2} = 0.693/k}$
Fraction left = $(1/2)^{\text{number of half-lives}}$

When answering multiple choice half-life questions try to estimate the answer first to eliminate improbable answers.

Dating Archaeological Samples

Ex. U-238 to Pb-206 ($t_{1/2} = 4.5\text{x}10^9$ yrs)
C-14 to N-14 ($t_{1/2}$ = 5730 yrs)

Age of the sample should be 0.3 to 3 half-lives of the isotope used for the dating.

Nuclear Fission: Any process that yields two nuclei of almost equivalent mass.

Requires that the fissile nucleus (i.e. one that is capable of fission) be bombarded with an energetic neutron.

This results in a chain reaction

U-235 + n → Br-87 + La-146 + 3n

Controlled by;

Samples less than critical mass (several pounds)
Absorption of neutrons by material such as graphite or paraffin.

Breeder Reactors: When U-238 or Th-232 are combined with fissionable isotopes they are converted to fissionable Pu-239 and U-233 respectively.

Nuclear Fusion:
The combination of two nuclei into a larger atom
Current research focuses on the reaction

$$\text{H-3} + \text{H-2} \rightarrow \text{He-4} + n$$

Cold Fusion - In *muon-catalyzed fusion*, the muon (same charge as electrons but 2000x more massive) takes the place of the electron around a hydrogen nucleus at a much tighter orbit, "neutralizing" the repulsive forces and allowing fusion to occur.
Unfortunately they are short lived and hard to come by, but current research is encouraging.

Biological Effects of Radiation:

Radiation damage from
1. Ionization of atoms (anemia, leukemia, etc.)
2. Mutation of molecules (can be passed on in DNA)

Mutagen = Able to induce mutations (changes) in DNA and other parts of living cells.
Teratogen = Growth abnormalities in embryos, genetic modifications in cells, etc.

The majority of exposure to radiation is from:
Natural sources (82%) of which 55% is from Radon. The other major natural source is natural radiation inside our body (e.g. C-14) (11%)

$$^{222}_{86}Rn \rightarrow {}^{218}_{84}Po + {}^{4}_{2}He$$

The half-life of Rn-222 is 3.8 days. Po and other "daughters" of the decay such as Pb-214 and Bi-214 are trapped in the lungs.
The ultimate source is the uranium content from rocks and minerals in the soil.
(The EPA safe limit of Radon is 0.15d/s/L)

The primary synthetic source of radiation is from medical X-rays (11%)

Penetrating Power of Radiation:

Alpha particles	stopped by	paper
Beta particles	stopped by	aluminum
Gamma rays	stopped by	several centimeters of lead

Activity Units:

curie	Ci	$3.7\text{x}10^{10}$ dps
becquerel	Bq	1.00 dps

Dosage Units:

Röentgen	R	deposition of $93.3\text{x}10^{-7}$ J per gram of tissue
radiation absorbed dose	rad	$1.00\text{x}10^{-5}$J absorbed per gram of material

(Roughly the energy absorbed by tissue exposed to one Röentgen of gamma rays.)

Röentgen	rem	the dose of any radiation that has the effect of 1 R

(Same biological effect in man as 1 rad of X-rays. This varies dependent upon the energy of the radiation.)
gray Gy 1.00 J/kg

Gamma radiation is the most penetrating, followed by beta and then alpha particles.

Measurement of Radioactive:
Geiger-Müller tube - Measures beta and gamma radiation by ionization chamber filled with argon. May also measure specific energy of radiation.

Cloud Chambers - Measures charged particles by condensation of cooled, saturated vapor. Electric fields determine charge (curved paths) while collisions determine mass.

Scintillation counters - Detects many different particles. Activity is determined with a phototube which picks up flashes from fluorescent chemicals mixed with the emitting substance.

Film Dosimeters - Film sensitive to different types of radiation worn as a plastic badge that can be analyzed for dosage received while in contact with radioactive materials.

Nuclear Binding Energy, Mass Defect and $E = mc^2$

It can be shown through nuclear physics that the mass of a nucleus is less than the sum of its component protons and neutrons. This difference, known as the mass defect, is the amount of mass that is converted into the nuclear binding energy that holds the nucleus together. The energy can be calculated through Einstein's $E = mc^2$ equation, where E is the energy in joules, m is the mass (in kg) and c is the speed of light (in m/s). This binding energy is also the energy necessary to separate the nucleus into its component parts.
Energy is sometimes represented in electron volts eV or megaelectronvolts MeV. An electron volt is the amount of energy gained by an electron when accelerated through a potential difference of 1 volt. The energy relationship is

$1eV = 1.6022x10^{-19}CV = 1.6022x10^{-19}J$ (Note: CV = coulombvolts)

It should be remembered that

-Mass lost in a nuclear reaction must be replaced by kinetic energy in the products.
-Mass gained in a nuclear reaction must come from the kinetic energy of the reactants.

Example Problems 2:

1. Given the nuclear masses
   $^{237}_{93}Np$ = 236.9970u $^{233}_{91}Pa$ = 232.9901u $^{4}_{2}He$ = 4.0015u
   Calculate the energy associated with the α decay of Neptunium-237, in MeV

2. Determine the energy requirement in MeV for the following nuclear reaction:
   $$^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{15}P + ^{1}_{0}n$$
   The atomic masses are Al-27, 26.9815u; He-4, 4.0026u; P-30, 29.9783u. Use 1.0087u for the mass of a neutron.

3. Cobalt-60 was involved in the worst radioactive accident in North America. The half-life of the isotope is 5.3 years. Starting with 10.0mg of Co-60, how much will remain after 21.2 years? Approximately how much will remain after a century?

4. A radioisotope disintegrates at the rate of 6400 counts per minute. 6.00 hours later, the disintegration rate is 1600 counts per minute. What is the half-life of the isotope?

5. A piece of charred bone found in the ruins of an American Indian village has a C-14 to C-12 ratio of 0.72 times that found in living organisms. Calculate the age of the bone fragment. (C-14 decays to nitrogen-14 with a half-life of $5.73x10^3$ years.)

Nuclear Chemistry Summary in Brief

Important Equations:

$A = \lambda N$ where A is the rate of radioactive decay, λ is the decay constant and N is the number of atoms present.

$N=N_oe^{-\lambda t}$ Remember: N is the amount that is left, not the amount decayed.

$ln(N_o/N_t)=\lambda t$ $ln(D_o/D_t)= \lambda t$ $ln(R_o/R_t)= \lambda t$

N = # of atoms, R = rate of decay, D = disintegrations per unit time.

$t_{1/2} = 0.693/\lambda$

Fraction left = $(1/2)^{\#\ half\text{-}lives}$

$E = mc^2$

$1eV = 1.6022x10^{-19}CV = 1.6022x10^{-19}J$

931.5MeV/u

Decay Processes:

High Z number = alpha decay
High N/P = beta emission
Low N/P = positron emission or electron capture
Think in terms of what will happen to the nucleus to bring the atom back to the "stability strip"

Elements with even proton and/or neutron numbers are the most stable.

Uranium is the last occurring natural element. Those beyond this are known as "transuranium" elements.

Bismuth is the last element w/ a stable isotope.

Many disintegration series end with Pb (206, 207 or 208)

In terms of damaging radiation:
Alpha decay is more dangerous internally than externally
Beta decay is more dangerous externally than internally
Radioisotopes with very long or short half-lives are less dangerous than those with intermediate values.
Gamma radiation is always dangerous.